Minnesota Department of Public Safety

Public Safety Wireless Data Network Requirements Project

Wireless Data Network Implementation Model

Phase 1-Task 7/Deliverable 5

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1 EXECUTIVE SUMMARY

This report is a deliverable for the State of Minnesota Public Safety Wireless Data Network Requirements Project. The deliverable requires Televate to "develop a sample regional implementation model for a wireless public safety data network based on the geographic region covered by the Southwest Regional Radio Board". The contract was later amended to extend the implementation model to the entire state. Additionally, Televate was tasked to include in the implementation model high level budget projections for both capital costs and operating expenditures and a list of assumptions upon which those projections are based and address any spectrum management and interference management issues that might be anticipated in the implementation model.

There are a variety of business models that may be feasible to achieve the public safety data needs in Minnesota. On the one extreme, a commercial carrier could deliver service without direct capital investment from the State. On the other extreme, the State could build and operate its own, dedicated infrastructure. In between, there are various levels of public/private partnerships that leverage various government and commercial assets. For example, the State could leverage the towers of the cellular carriers or the State could leverage commercial services where they exist. Within the Carrier Assessment Report, it was documented that there were multiple potential risks with public/private partnership models and it is currently unclear if the State's system reliability and network access requirements could be met with this model. It also reported that the pure commercial model did not meet the requirements of the State public safety officials. Therefore, Televate recommends an open approach to investigate the viability of various operational broadband models through a formal Request for Proposal (RFP) process. As a baseline for estimating the high-end cost for a statewide implementation, the implementation model selected for this report is a completely private and dedicated network. This private model can also provide perspective on the cost of the various public/private models.

The model includes a preliminary design of a statewide broadband network. The preliminary design is intended as a budgetary design to establish the quantity of sites required to meet the coverage and capacity requirements of the state. The design uses existing State assets to the greatest extent possible. The primary asset used in the model is ARMER[1] existing radio sites. Wherever ARMER sites are not available, a new tower is proposed. The model also leverages the State's existing fiber backbone and generators at existing ARMER sites[2]. The broadband data network model includes a 700 MHz Long Term Evolution (LTE) Radio Access Network (RAN) and redundant Evolved Packet Cores (EPC) that meets the coverage and capacity requirements identified in the User Needs Assessment; redundant Microwave backhaul system that supports both day-to-day and incident traffic models; fiber optic broadband connectivity using existing fiber facilities from each microwave ring to the two EPCs; and towers and generators for all new (non ARMER) sites. The model assumes the operations of the network mirror the ARMER model and leverage the existing State operations resources.

The budgetary network design is based on the requirements drawn from our analysis of the needs expressed by users and documented in the Needs Assessment Report[3]. These requirements include

[1] Allied Radio Matrix for Emergency Response (ARMER) is the statewide Project 25 land mobile radio network.

[2] In the final design, the State should investigate the availability of local and county jurisdiction asset.

[3] Needs Assessment Report, Phase 1-Task 4/Deliverable 2

rural and urban data throughput levels to accommodate day-to-day and public safety incident traffic. They also include in-building coverage objectives for urban areas, portable on-hip coverage in suburban areas, and mobile vehicular coverage in rural Minnesota. The urban and suburban coverage levels are anticipated to be lower than that of commercial services today[4]. These coverage levels are required over 95 percent of each county in the State. Finally, the requirements also specify a public safety hardened system, and therefore, there are multiple redundant elements in the design.

The statewide LTE system requires 521 three-sector cell sites (eNodeBs) to achieve the coverage and capacity needs identified by the State. Of the cell sites, 380 are current or planned ARMER sites and 141 are new sites. Of these new sites, 93 assume 250 feet towers serving the more rural areas while the remaining 48 assume 150 feet towers serving the metro areas. The two Evolved Packet Cores are fully redundant and housed at geographically separated hardened facilities[5].

In response to State objectives, a full backhaul plan was engineered for the Southwest Region and high-level assumptions based on the Southwest Region design were extrapolated through the remainder of the State. The Southwest backhaul plan includes seven microwave rings that are connected to a Mn/DOT fiber ring that provides dual path redundancy to all cell sites in the region. There are no more than seven cell sites engineered onto a single microwave ring. Each ring's capacity is designed to support 100 Mbps in the urban areas and 45 Mbps in the rural areas to accommodate the expected traffic density. The microwave rings are connected to OET's fiber backbone at three points of presences (POPs) within the region. The financial models for the remaining regions assume that a fiber ring is available to the microwave rings in the same manner.

The cost model leverages, to the greatest extent possible, historical capital and operational cost estimates from the ARMER build out. The costs include the new network equipment, site improvements, tower construction, and the services associated with the build-out (e.g., project management, engineering, site acquisition). The remaining costs are based on Televate's experience in the public safety broadband marketplace. The total cost of the Private Service model is summarized in the following table:

Table 1: Cost of the Private Implementation Model

Expenditures	ARMER PLUS (521 Sites)	ARMER (380 Sites)
Radio Access Network (RAN) and Backhaul	$ 310,717,004	$ 182,828,703
Core Network	$ 21,419,800	$ 19,994,200
Total Capital	$ 332,136,804	$ 202,822,903
Annual Operational Expenditures	$ 14,078,275	$ 13,077,350

[4] The commercial carriers are estimated to have approximately 4,300 cell sites throughout the State with the vast majority in the metro areas, inclusive of all operators.

[5] It is important to note that a redundant core could also be located in a neighboring state or elsewhere in the nation.

In addition, to these scenarios, Televate investigated the possibility of reducing the capital expenditures by leveraging the fiber networks of the State and county agencies; referred to as the “OET” model. Televate hosted a series of meetings with OET and selected counties to determine the location of the points of presences (POPs) on their network. We overlaid this information over the two ARMER design scenarios and established the number of ARMER sites where fiber exists, then transposed these estimated percentages statewide. The end result of the analysis is to reduce the number of microwave connections, and correspondingly the cost associated with supporting the fiber backhaul connectivity increased. The estimates for these scenarios are in the following table:

Table 2: Cost of the Private OET Implementation Model

Expenditures	OET ARMER PLUS (521)	OET ARMER (380 Sites)
Radio Access Network (RAN) and Backhaul	$ 293,324,458	$ 165,436,156
Core Network	$ 21,419,800	$ 19,994,200
Total Capital	$ 314,744,258	$ 185,430,356
Annual Operational Expenditures	$ 15,910,930	$ 14,910,005

For both models the capital expenditures decrease by $17, 392,547.00; a decrease of 6 percent. The operational expenditures increase by $1,832,655.00, an increase of 12 percent due to the added cost of connectivity provided by OET.

All costs are calculated based on the current cost for services and hardware, circa 2011[6]. The table depicts the costs of two distinct private build models: one that meets the state’s requirements, and one optimized for cost. Not surprisingly, a substantial portion of the costs is based on the 141 new sites. In those occasions, a new tower, supporting site acquisition and other costs are required along with LTE electronics and microwave backhaul. The analysis illustrates that nearly 95 percent of the State is covered at the required throughput levels using only the ARMER sites, but 28 counties had less than 95 percent coverage individually. This configuration leaves significant portions of rural Minnesota uncovered at the required broadband levels. But because LTE can scale down data throughput to lower speeds at the lower signal levels, only a handful of counties would not reach 95% coverage with low-speed data throughput levels (32 kbps) capable of supporting applications such as text messaging and dispatch data. These different options present perspective on the costs versus requirements. Other intermediate options are possible; however, they have not been designed or budgeted.

The full system, as designed, supports more than 312,000 day-to-day users (i.e., excluding major incident traffic). This means that up to that subscriber average usage level, the operations costs of the network are largely fixed. Therefore, comparing the per-user operations costs of a private network to commercial services depends on the quantity of users on the statewide network. The analysis shows

[6] Costs for some items will likely increase over time (examples include: professional and installation services, commodities, land and rents; however, some prices may decrease in real term over time, these examples include LTE equipment, software, network equipment and other consumer electronic hardware.

that assuming a $42.99 per month commercial fee ($46.27 for 4G LTE services inclusive of sales tax), the ARMER PLUS network (521 sites) would require approximately 63,694 users to “break-even” (i.e., incur the same net cost); inclusive of the amortization costs, and 25,356 users without amortization. In contrast, the ARMER model (380 sites) would require 49,387 users to breakeven with amortization and 23,554 without. However, there are three critical assumptions in this figure: first, it assumes that the commercial rate will remain at $42.99 per month where it has been shown to be on a continual decline, but second, it assumes that rate would apply to high priority service from the carriers – something they are likely to charge a premium for, and third, it assumes that the statewide private network meets the necessary functions of the commercial networks (devices, in-building coverage, etc.). The first two assumptions could balance out over time and have a neutral cost impact and the third assumption could dramatically influence the real quantity of users or devices that could be serviced by the private network.

The Private Service implementation model then places an interim perspective on the high-end capital costs required to achieve the State’s public safety wireless data requirements. The model requires a substantial investment, which, given the State’s current fiscal situation, would be a challenge to fund. It does shed light, however, on hybrid model approaches that could cost substantially less.

2 Introduction

This report is a deliverable for contract #B51065 for Public Safety Wireless Data Network Requirement Project. The scope of work calls for Televate to “Develop a sample regional implementation model for a wireless public safety data network using the geographic region covered by the Southwest Regional Radio Board. The implementation model should contain high level budget projections for both capital costs and operating costs and a list of assumptions upon which those projections are based and should address any spectrum management and interference management issues that might be anticipated in the implementation model.” The contract was later amended to include a second phase to extend the implementation model to the entire State of Minnesota. A detailed statewide backhaul design on a site-by-site basis was outside the scope of the project.

3 Business Models

Three types of wireless broadband implementation models can be considered for the State of Minnesota. The models can be a combination of a number of different options.

- Commercial Service: The State could leverage turnkey commercial services/networks wherever they are available and avoid direct capital investment altogether.

- Private/Public Models: The State could leverage various elements of commercial carrier networks such as their Evolved Packet Core or their cell towers to reduce the capital cost associated with the network. The State could also leverage the commercial network where it exists and build out coverage using the public safety band wherever the commercial carriers do not.

- Private Service: The State could build a complete and wholly owned and controlled private infrastructure. The sites could leverage commercial towers wherever available.

During the course of the project, as the needs of the users were assessed, and future 4G service plans of commercial carriers in the State of Minnesota were evaluated, it became apparent that Commercial Services present a number of challenges:

- Major carriers don't currently have statewide coverage, 4G or otherwise, to include the required county-by-county coverage -- especially in rural areas.
- An analysis of the cellular industry indicates that they may not be able to accommodate the public safety priority of traffic as well as pre-emption over other commercial traffic.
- Commercial carriers will have difficulty meeting the network reliability required by the Public Safety applications.

These issues are Radio Access Network (RAN) related. In other words, the primary inadequacy in commercial capabilities is with the RAN. The RAN makes up the majority of network construction and operations costs, and therefore, the most substantial benefits of a public/private partnership occur if the State uses the commercial RAN. Therefore, in order to address the worst-case scenario that a commercial carrier cannot meet the State's requirements, the model presented herein is entirely a Private Service model. The financial models will, however, provide a rough order of magnitude perspective of cost for other hybrid models.

4 System Requirements

The following sections detail the requirements for the system. They are derived primarily from the Needs Assessment conducted by Televate in January 2011. They also include other requirements as specified by the FCC and industry best practices. In a LTE system, coverage and capacity go hand-in-hand due to the increasing levels of interference experienced at increased capacity loads. Therefore, it is difficult to differentiate the two attributes. Televate defines coverage as the service area over which an individual user can experience an acceptable quality of service while leaving sufficient communication resources for other users. Therefore, a coverage map defines those locations that will meet the minimum throughput requirements. We define capacity as the raw throughput available to all users of a given cell site (sector). We determine the spot capacity (at one location on a map), by considering the signal-to-noise ratio at that location with the noise varying depending on the conditions at adjacent cell sites. The pass-fail criteria for capacity is then defined as those locations that meet the aggregate throughput needs for all users that would operate in a given cell site's sector.

4.1 RAN Coverage Requirements

The needs of an individual user in the system are a function of the applications the user will need to access. Single user requirements define the sum of throughputs of all individual applications used by a user at the same time. The Needs Assessment Report defines public safety applications and use cases that the network needs to support. They vary from a few kilobits per second for Automatic Vehicle Location to more than 1,000 kilobits per second for a high resolution video stream.

Given these requirements, the network should support at least 253 kbps at the application layer, in the downlink and uplink. This corresponds to the data rates required to transmit and receive a single low resolution video stream by a single user. However, the throughput requirements should take into consideration Federal mandates. FCC 700 MHz waiver recipients are required to provide coverage at data rates of 256 Kbps uplink (UL) and 768 Kbps downlink (DL). These requirements are consistent with Federal grant requirements for programs such as Broadband Technology Opportunities Program (BTOP). To ensure that the network can service additional users, Televate assumes the requirements must be met with no more than 16 percent of a sector's resources – allowing more than five other users in the same sector at the same throughput.

The coverage requirements must also define the area over which service is provided and the local environment of the user. In the case of the service area, the State defined that 95 percent of every county to receive the required level of service. And in the case of the user environment, the State required three levels: in-building (hip worn) coverage in the cities, outdoor hip-worn coverage in the suburban areas, and mobile coverage in Greater Minnesota. The specific coverage requirements for the statewide design are summarized as follows:

Table 3: Summary of Coverage Requirements

Area	UL Throughput Required (	DL Throughput Required (	Coverage Level	Coverage Area Availability Target
Greater Minnesota	256	933	Mobile Coverage	95% County by County
Hennepin County	256	1437	Outdoor hip-worn device	95% County by County
Ramsey County				95% County by County
Washington County				95% County by County
Anoka County				95% County by County
Isanti County				95% County by County
Sherburne County				95% County by County
Wright County				95% County by County
Carver County				95% County by County
Scott County				95% County by County
Dakota County				95% County by County
Minneapolis	256	1437	in-building coverage	95% City by City
St. Paul				95% City by City
Rochester				95% City by City
Duluth				95% City by City
St. Cloud				95% City by City

The in-building coverage requirement is defined as within the city limits plus an additional 5 miles. Note that 95 percent coverage reliability requirement is consistent with public safety standards and the recently released FCC-ERIC recommendations. In rural areas, where only the outdoor coverage is required, Televate's preliminary design used sites in closest proximity to major towns where possible to achieve in-building coverage.

4.2 RAN Capacity Requirements

While LTE delivers continuously improving throughput and performance, its capacity is limited. The bottleneck of an LTE system is the sector since all users in the service area of a sector share its capacity. The typical cell site houses three sectors. The bandwidth available to a user is highest where the signal level, and the ratio of that signal to the noise and interference from other cells, is highest. The quality of service of a broadband system depends on the number of users in a sector, where they are located, what demand (kilobits per second) each user places on the network, and the interference (noise) caused by users in other sectors in the network.

The aggregate capacity requirements of a single sector are then a function of the total traffic offered in a given area. Due to the in-building coverage requirements stated above, the site density, and therefore, the coverage area per sector, is smaller in the metro areas. In the case of the proposed design, the coverage area of a sector varies from four square miles in the urban areas to 67 square miles in rural areas. The traffic that must be carried by a sector must include both the day-to-day traffic and that associated with a major public safety incident. The following sections outline the impacts of both types of traffic.

4.2.1 Incident Scenario Throughput Requirements

The capacity of the network must accommodate the user needs at major incidents. A substantial amount of usage in a small area is the most challenging scenario for a wireless broadband network. For instance, the area of the incident addressed in the Needs Assessment was only 640 feet by 950 feet (0.02 square miles) and required the following throughput levels:

Table 4: Application Throughput Requirements

Scenario	Downlink (kbps)	Uplink (kbps)
Urban Area (Short-Term)	3,849	623
Urban Area (Long-Term)	7,596	4,298
Rural Area	2,509	197

The table depicts a short and long-term throughput requirement for the “active shooter” scenario of the Needs Assessment as well as routine loading nearby. The short-term need accommodates existing technology and the feasibility of the deployment of other easily deployable technologies. The long-term scenario includes foreseeable and desired technologies such as streaming video from helmet cameras. In the initial deployment phase, the network may only support 623 kbps on the uplink and 3849 kbps on the downlink. The long-term capacity requirement was viewed to be as many as 5 to 10 years out.

The rural incident is thought to have a lesser concentration and usage of first responders, and therefore, it is expected that the incident will only require 2,509 kbps in the downlink and 197 kbps in the uplink. The capacity requirement for the long term rural scenario is not expected to change significant beyond the short term scenario.

4.2.2 Day-to-Day Requirements

In addition to the incident demand, the network must also accommodate day-to-day or routine traffic of the state's public safety personnel. Most of the users on the LTE network are expected to be laptop or mobile users, the heaviest data consumers on commercial networks. Today carriers put a cap on data usage; for example, Verizon Wireless' data cap begins at 2 Gigabytes (GB) per month per user[7]. Televate assumes that the routine public safety traffic will be consistent with this cap (and be additive to the incident traffic). To put 5 GB in perspective, a public safety user with similar data consumption would be able to stream up to sixteen videos[8] of twenty minutes long each month. Assuming there are 11 and 40 users[9] per sector in rural area and urban area respectively, we can estimate the typical backhaul link capacity required. That capacity includes the traffic generated by major incidents, which derived from the incident scenario analysis. Table 4 below shows the expected day-to-day load assuming uniform distribution of traffic throughout an eight hour day.

Table 5: Day-to-Day Capacity Requirements

	Rural Area	Metro
Typical Monthly Traffic	5GB	5GB
Number of Users per Sector	11	40
Number of work hours per day	8	8
Day-to-day Traffic Per Site	2.4 Mbps	8.4 Mbps

4.2.3 Summary Performance Requirements

Design and capacity dimensioning of the LTE network is based on the data throughput requirements at the physical layer. Overhead added by signaling on the physical layer, Internet Protocol headers, and other sources requires more throughput on the physical layer. The net overhead depends on the type of traffic, packet sizes, and other factors such as interference and terminal performance. Televate assumed 12 percent total overhead on top of the application rates specified in the Needs Assessment report to arrive at the net physical layer requirement[10]. The throughputs required by FCC are defined at the physical layer and therefore can be used as is in the design and dimensioning of the network.

Based on the above findings, the performance requirements on the LTE physical layer are summarized, taking into account the 12 percent signaling and higher layers overhead:

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[7] See for example http://support.verizonwireless.com/faqs/Calling%20Plans/data_package.html

[8] This assumes a low resolution video of 256 kbps

[9] This assumption is based on the estimate user distribution (from stakeholder's survey) and site densities obtained from the proposed LTE preliminary design.

[10] See "The LTE Link-Layer Design", Anna Larmo & al (Ericsson Research), IEEE Communications Magazine, April 2009

Table 6: LTE Physical Layer Requirements

Physical Layer Requirements	Downlink (kbps)	Uplink (kbps)
Urban Area (Short-Term)	4,311	698
Urban Area (Long-Term)	8,508	4,814
Rural Area	2,810	220

The manner in which these theoretical incidents impact a single sector's capacity is more complex. The incident could occur at the intersection of two or more sectors' coverage or it could be encompassed by the coverage of a single sector. The sector's capacity is also a function of the loading in the adjacent sectors. Adjacent sectors could host normal day-to-day traffic, or there could be other incidents occurring in these sectors. Televate investigated both scenarios. Most LTE equipment vendors estimate that a cell using 2x2 MIMO would provide a median downlink capacity of 13 Mbps per cell[11] with a 10 megahertz channel[12].. The incident downlink throughput of 4,311 kbps is then 33 percent of the median sector (cell) capacity. If the incident occurs at cell edge, Televate estimates that, based upon 3GPP simulations, the available capacity would then be reduced to 30 percent of the median or approximately 3.9 Mbps on the downlink. Under this scenario, the available capacity at the cell edge would be sufficient for the rural area requirements but not meet the urban area capacity requirements; 91 percent of the anticipate load would be served under the "short-term" urban scenario and less than 47 percent served under the "long-term" scenario.

In the FCC White Paper[13], the FCC formulated several scenarios where that traffic was spread over coverage areas of different sizes; ten, five, and one square miles in separate studies. In the case of the one square mile scenario, the FCC assumed six sectors (two eNodeBs) would carry the traffic, equating to 0.5 square miles per site[14]. Given this scenario, the FCC assumed that the load could be evenly distributed, each sector carrying 3.5 Mbps for downlink and 2.1 for uplink. In Televate's model, given that the incident is very small compared to the coverage of a sector; it is unrealistic to assume that six sectors can overlap at the incident scene.

The incident capacity can be increase by cell splitting; adding new sites at the cell edges of existing sites for greater coverage and overall network capacity. A denser network where the cell coverage area is smaller than the incident area, would distribute the traffic across more sectors as projected in the FCC model. Clearly, a higher cell density would require more capital and operations funding. The other alternative would be to engage vendors to propose more spectrally efficient performance techniques that are capable of improving the cell edge performance sufficiently to meet the required demand.

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[11] Based on capacity simulations performed by Televate using uniform traffic distributions and realistic deployment scenarios.

[12] Assuming 20MHz total or 10MHz paired

[13] The Public Safety Nationwide Interoperable Broadband Network: A New Model for Capacity, Performance and Cost, June 2010. See http://fcc.gov/pshs/docs/releases/DOC-298799A1.pdf page 26.

[14] The Televate design covers roughly 2.5 square miles per site, and therefore, the FCC assumed build out is five times denser than the Televate design.

4.3 Backhaul Capacity Requirements

The backhaul system must accommodate the aggregate need of all cell sites in the system and carry it to the Evolved Packet Core. Therefore, the backhaul must provide sufficient bandwidth to cover day-to-day traffic needs as well as major public safety incidents. Furthermore, the backhaul design must accommodate failure scenarios such that if a link fails, the capacity is sufficient to carry the traffic back. Therefore, the microwave rings must be able to accommodate traffic flowing all the way around the ring in the event of such a failure.

Table 7: Microwave Links Dimensioning

	Rural Area	Metro Area
Day-to-day Traffic Per Site	2.4 Mbps	8.4 Mbps
Traffic per incident	2.5 Mbps	7.6 Mbps
Number of sites covering an incident	1	1
Number of Incidents in a MW ring	3	3

It should be noted that the typical capacity limit of three-sector LTE site is 40 to 44 Mbps in a 2x10 MHz spectrum allocation (roughly 13 Mbps per sector). The table above illustrates that the expected public safety demand is well below these levels on a per site basis. This is because it is very unlikely that all sites in a ring will be loaded at maximum capacity simultaneously[15]. Instead, the model assumes that three incidents are loaded on three sectors in the ring. Using the results of this calculation microwave links were designed at 30Mbps and 100Mbps in rural and urban area respectively to allow for some growth. It is important to note that the throughput requirements expressed above for a ring represent the failure scenario. Under normal conditions an MPLS based network would provide far more excess capacity for other applications.

4.4 Reliability

The system is designed to 99.999 percent availability. In order to achieve this level of availability, the system was designed to a high reliability with multiple redundancies. This includes a redundant Evolved Packet Core outside of the Twin Cities metro area. The contract calls for a backhaul design in the Southwest Region only. That design includes at least two diverse paths from every cell site to the two Evolved Packet Cores. This includes a multiple ring topology. The first ring interconnects the cell sites using microwave links. Each link itself is designed to 99.9999 percent reliability with a maximum of seven links per ring for increased reliability and reduced latency. The system includes a Multi-Protocol Label Switching (MPLS) system that can instantly route around any failures and determine the best routes (e.g., based on latency). Each microwave ring is interconnected with the statewide fiber ring allowing each site to connect to two points on the fiber ring. The same principles are recommended for the statewide design.

[15] In other words, it would be unlikely that multiple sites would be heavily loaded at the same time.

5 SYSTEM DESIGN

The following sections provide details on the system architecture. The following figure represents the high level architecture of the proposed design:

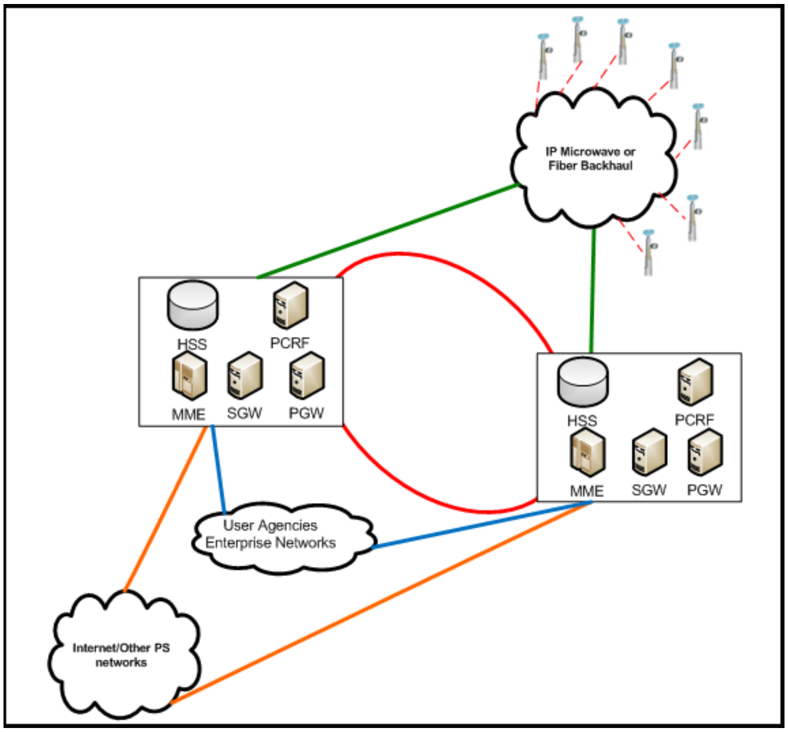

Figure 1: High-Level Network Architecture

5.1 Radio Network Design Process

The eNodeB provides the LTE user with over-the-air access to the LTE network. Therefore, the distribution and design of the eNodeBs dictate the service levels delivered to the user. LTE throughput performance of is a function of the signal-to-noise ratio and the amount of offered demand. Unlike Land Mobile Radio (LMR) systems, LTE uses the same frequencies in every sector (typically, there are three sectors per eNodeB serving a different area from the cell site). Each adjacent sector is a potential source of interference. Therefore, any LTE design needs to minimize overlap between sectors to the greatest extent possible. Televate's preliminary design for the State of Minnesota network seeks to minimize the cost of deployment by maximizing the use of the State's ARMER facilities. Use of existing State towers avoids the capital cost of building new towers as well as reducing the long-term operational cost of a site lease.

Televate's design approach first considers the link budget associated with the target usage scenario(s). The link budget defines the maximum path loss that can be incurred in order to achieve the desired throughput. Using the link budget results, Televate evaluates the preferred site candidates and determines their ability to meet the minimum throughput levels over the defined coverage area without selecting sites that would negatively impact the system performance (i.e., extraordinary tall sites that would pose too great a risk of interference). This step incorporates an iterative process whereby the ideal constellation of sites was chosen. Through this process, Televate created a budgetary design that achieved the coverage objectives outlined above while minimizing non-ARMER facilities.

5.1.1 Spectrum and Interference

The implementation model assumes the network will utilize LTE Band Class 14 (758-768 and 788-798 MHz) designated by the Third Generation Partnership Project (3GPP). The design assumes that a single 10 MHz channel is re-used at every cell site. It does not account for the interference from any future neighboring system, outside the State, operating in the same frequency band. The design does not account for any Canadian border constraints. Presumably, Canada will utilize the same frequencies and technology as the United States, and therefore, interference mitigation becomes far simpler. In fact, handoff between cell sites along the border becomes feasible and desired to mitigate the impacts of interference. In the event that Canada deploys a disparate technology or rules otherwise require power reductions, the northern tier of cell sites would require a re-design that would impact their coverage and cause more cell sites to achieve the desired coverage.

5.1.2 Link Budget

In the design of any radio system the link budget is used to evaluate the maximum propagation loss between the transmitter and the receiver to achieve a certain link quality and throughput. Link budgets are calculated for both the downlink (base station to end-user device) and the uplink (end-user device to base station). In the case of LTE, the eNodeB (base station) transmits at much higher than the User Equipment (20 Watts versus 200 mW) and the downlink path can accommodate more loss than the uplink. Therefore, the uplink represents the worst-case path and the Televate design is based on uplink coverage.

Televate's link budget accounts for all system losses and gains. Specifically, it addresses signal fading, noise levels from adjacent sites, building loss, and other environmental losses. Televate's design assumes a fade margin to accommodate a coverage reliability of 95 percent. For hip-worn service level the link budget assumes a body loss of six decibels (dB). In urban areas where in-building service is required Televate's link budget assumes an additional 20 dB of building penetration loss. The link budget also includes a gain from the use of diversity receive, whereby the best signal arriving at multiple antennas is used at any instant.

The link budget also accommodates the disparity between uplink and downlink receiver sensitivity. Given the same signal-to-noise ratio, the downlink path (i.e., from the eNodeB to the UE) can achieve higher throughput; there is a net performance disadvantage in the uplink. As the uplink is the weaker path and is disadvantaged because of its limited output power, it is used as the reference for predicting whether service will be available at any location. In other words, where the prediction maps depict service on the uplink, there is service on the downlink. The target signal levels are, in turn, incorporated in to Televate's broadband wireless software tool to estimate coverage for the uplink[16].

[16] Note that the uplink is the limiting factor for coverage, and therefore, areas covered by the uplink are also covered by the downlink.

The use of Multiple Input Multiple Output (MIMO) can impact the link budget because it allows the same wireless resource to be reused for each antenna. Performance gains due to MIMO depend on antennas that are spaced ideally at the UE location, which may not be always possible, especially in the case of a USB modem. Televate assumed conservative gains from MIMO in its models.

5.1.3 Software Modeling

Televate uses the industry accepted Anderson 2D (two dimensional) propagation model to estimate path loss between the cell site and the user device. The model incorporates losses that would be incurred by terrain before the signal would arrive at any location. The model also includes empirical losses due to blockage by buildings and trees that would cause additional signal losses between the cell site and the user. To account for this blockage, the model employs land use maps provided by the United States Geological Survey (USGS).

The standard cell site configuration in the design is as follows:

- Cell Site Output Power: 20 Watts
- Cell Site Antenna gain and height: 16 dBi / 6ft
- Cell Site Cable losses: 2.5 dB
- Mobile antenna gain: 0 dBi
- Mobile output power: 200 mW
- Standard three sector configuration: 0, 120, and 240 degrees from True North
- Antenna height Above ground:
  - For existing ARMER sites: At rooftop or 10ft below tower height[17]
  - For new sites in rural areas: 250ft
  - For new sites in Metro region: 150ft[18]
- User equipment height above ground: 5 feet
- MIMO: 2x2 (with diversity gain on the uplink)

5.1.4 eNodeB Site Selection

Televate incorporates the requirements listed above as well as sound engineering assumptions to develop the budgetary design. In selecting sites for the coverage design, Televate gave special consideration to ARMER sites and other towers provided by Mn/DOT. The iterative process first leverages existing ARMER assets to minimize capital and operations cost and to speed a potential deployment. Using these sites, Televate identified initial coverage holes. From that point, per the direction of the State, Televate selected green-field sites to provide the required coverage levels.

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[17] Televate assumed that the chosen height was available and the tower can accommodate the load.

[18] In a cursory review of the commercial tower databases, it appears that a number of existing commercial towers at this height. However, if it is not feasible to build towers at this height, more, shorter towers would likely be required.

Where possible, the design situated new sites close to population centers to maximize in-building coverage in cities and towns.

The design is a budgetary design. It is intended to determine the approximate quantity of sites required to satisfy the State's broadband wireless coverage requirements. There was no effort to ensure that new sites were situated near roads or existing power, nor was there an effort to understand local zoning and permitting rules to determine the feasibility of building new towers in these locations. These factors, or required reductions in tower height, could result in an increase in the number of sites required to achieve the required coverage.

5.1.5 Backhaul Design

After selecting the ideal sites based on LTE coverage, Televate created a backhaul design that connects each cell site to the core network. The design was created in ring format to ensure redundant interconnection to the core network. Link analysis was performed for each interconnection which consisted of a link budget analysis, capacity analysis and point-to-point profile analysis. Aggregation points were identified on existing MNET fiber ring maps. As defined in the scope of work, a detailed backhaul design was performed for the Southwest region and the economic impacts of that design were extrapolated to the remainder of the State.

5.2 RAN Design

5.2.1 RAN Design Overview

Of the 394 sites listed in the ARMER sites file provided by the State, 380 were used in the implementation model design. Others were duplicates or too close to other selected site locations. A combination of the existing sites and new sites in the preliminary design provides over 95 percent of coverage statewide and 95 percent in each county.

Figure 2 shows in yellow the existing ARMER facilities used in the design and in blue the proposed new sites locations.

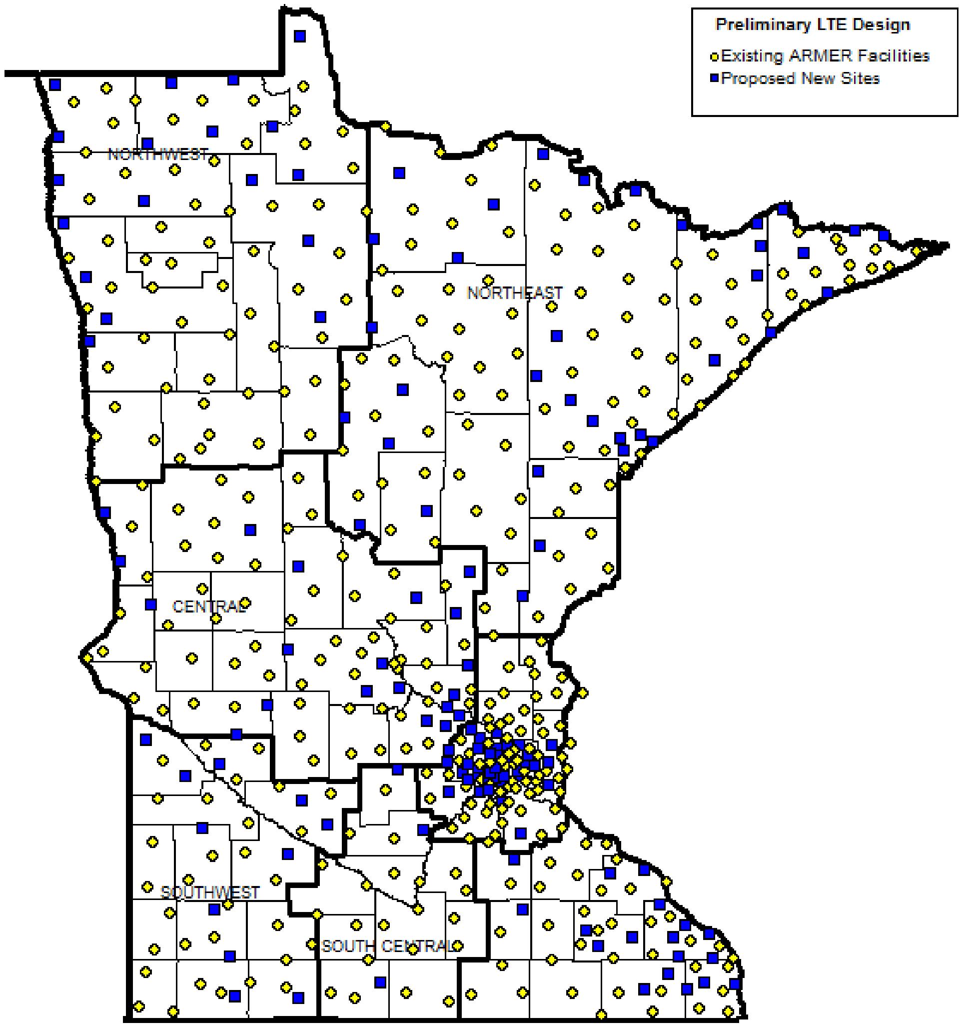

Figure 2: Preliminary Design Sites Distribution

The following table provides the number of sites in each category.

Table 8: Site Count

Site Priority	Count
Stated Owned ARMER Sites	325
Leased ARMER Sites	55
New Sites	141
Total	521

The table shows that 27 percent more sites were needed to satisfy the broadband throughput requirements. The primary reason for this increase in sites is due to the lower power levels of the LTE subscriber device – an LMR portable radio transmits at more than 10 times the power of an LTE device. This factor has dramatic impacts on the coverage between LMR and LTE.

The following table shows the geographical distribution of site location in the design.

Table 9: Geographic Distribution of LTE Sites per Region

Region	ARMER Sites	New Sites	Total	Percent New
Central	63	20	83	24%
Metro	70	36	106	34%
Northeast	97	35	132	27%
Northwest	59	18	77	23%
South Central	20	3	23	13%
Southeast	39	18	57	32%
Southwest	32	11	43	26%
Total	380	141	521	27%

The majority of new sites are required to meet the 95 percent coverage threshold requirement on a county-by-county basis. For example, this translates to nearly one third more towers in the Southeast Region due to the rough terrain that reduces the range of radio sites. The Twin Cities metro area also required one third more sites, but this was due to the need to provide in-building coverage rather than the mobile coverage ARMER objective. In building coverage problems may be mitigated by local and city ordinances that require the building owner to provide a distributed antenna system (DAS). In the final design, the State may decide to restrict the coverage to areas where the LTE coverage is needed. This will greatly reduce the number of sites, and consequently the capital and operational costs. And finally, the state could relax the data speed requirements in certain areas of the state. This scenario is discussed in more detail below.

5.2.2 Complete County Coverage RAN Design

Figure 3 depicts the estimated statewide coverage of the preliminary design. Green represents the Portable Coverage and Yellow the Mobile Coverage. The areas colored red represent where neither target throughput requirement is being met.

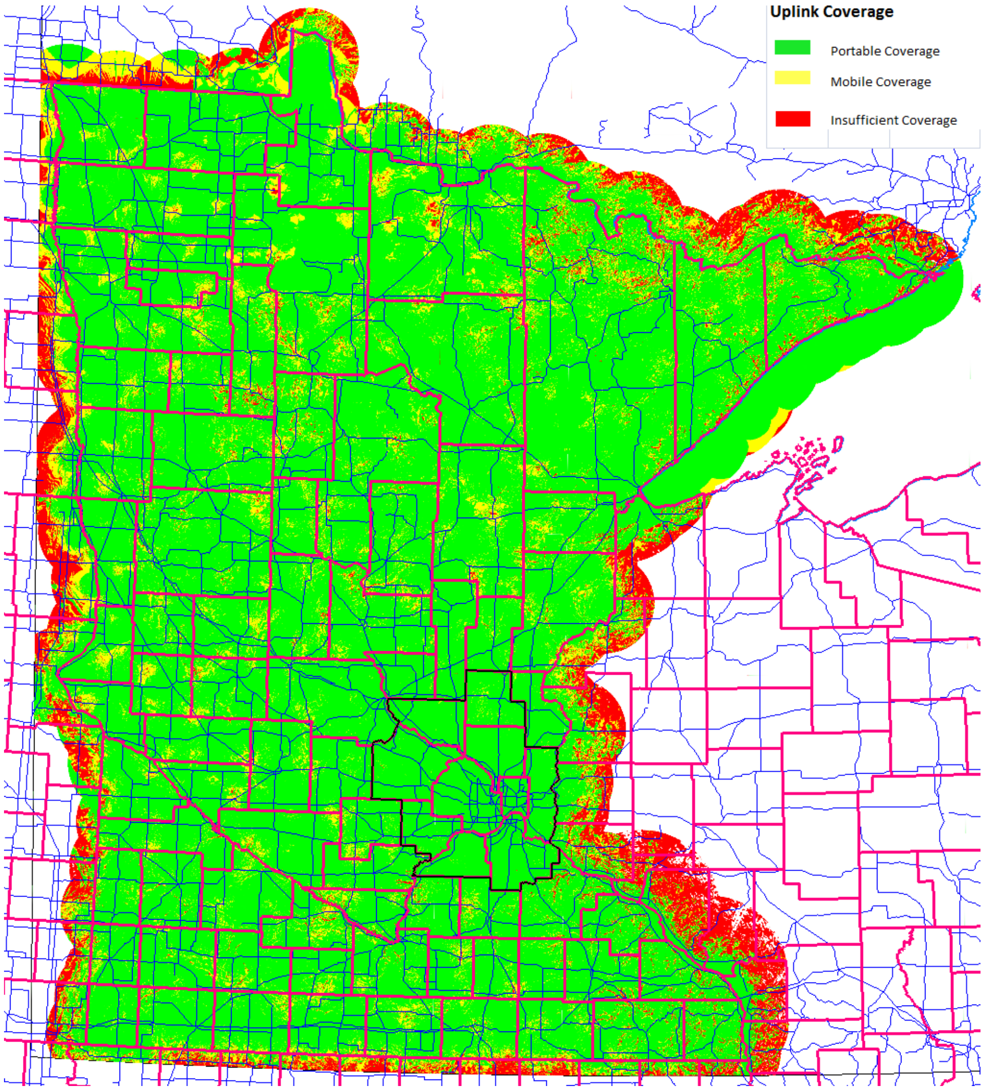

Figure 3: Statewide LTE Uplink Coverage

The map illustrates that there are very few areas where we do not achieve outdoor mobile levels of coverage for the target throughput. Detailed statistics are available in the Appendix. The following table provides the high level statistics of the design:

Table 10: LTE Design Coverage Statistics

Coverage Area	Coverage Availability	Coverage Type
Greater Minnesota	More than 95 percent in each County	Outdoor Mobile Coverage
Hennepin **Ramsey** **Washington** **Anoka** **Isanti** **Sherburne** **Wright** **Carver** **Scott** **Dakota**	99% 99% 98% 98% 95% 98% 98% 98% 99% 99%	Hip-Worn Device Coverage
Minneapolis **St Paul** **Rochester** **Duluth** **St. Cloud**	98% 97% 96% 95% 97%	In-Building Coverage

The table provides the coverage percentage for hip-worn and in-building hand-held devices within the Twin Cities areas. The figure below represents a map of the hip-worn coverage (in green) in the nine county Twin Cities area.

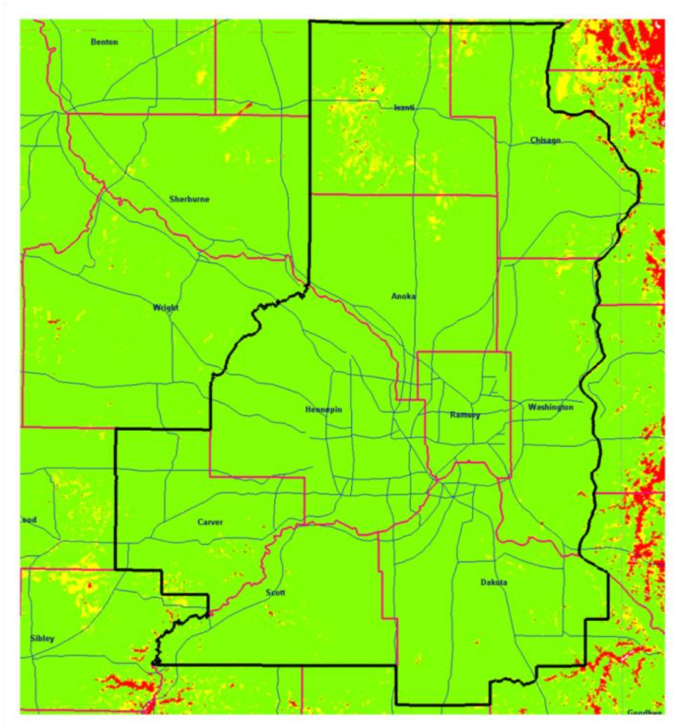

Figure 4: Hip-Worn LTE Coverage

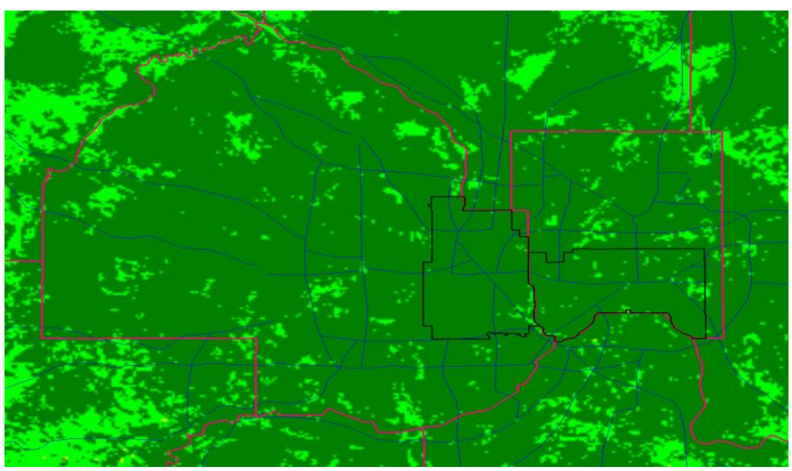

Figure 5: In-Building Coverage in the Metro

Figure 5 above depicts (in dark green) the in-building coverage in the Twin Cities. The preliminary design provides in-building coverage in more than 95 percent of the geographic area within the limits of each of the five major cities (Minneapolis, St Paul, St Cloud, Duluth, and Rochester).

5.2.3 ARMER Sites Only RAN Design

Televate also considered a design option using only ARMER P25 sites. This eliminates 141 sites from the design that are modeled as new tower construction. Eliminating these sites from the design reduces the overall cost of the build by approximately 37 percent. Televate estimates that a 380 ARMER site system ("ARMER Only Design") can provide mobile coverage in 94 percent of the State at the BTOP "broadband" speeds. Figure 6 below depicts the coverage statewide using only these ARMER sites. The map shows multiple large holes – particularly in the North at "broadband" speeds. While many counties meet the 95 percent coverage criteria, 28 counties do not.

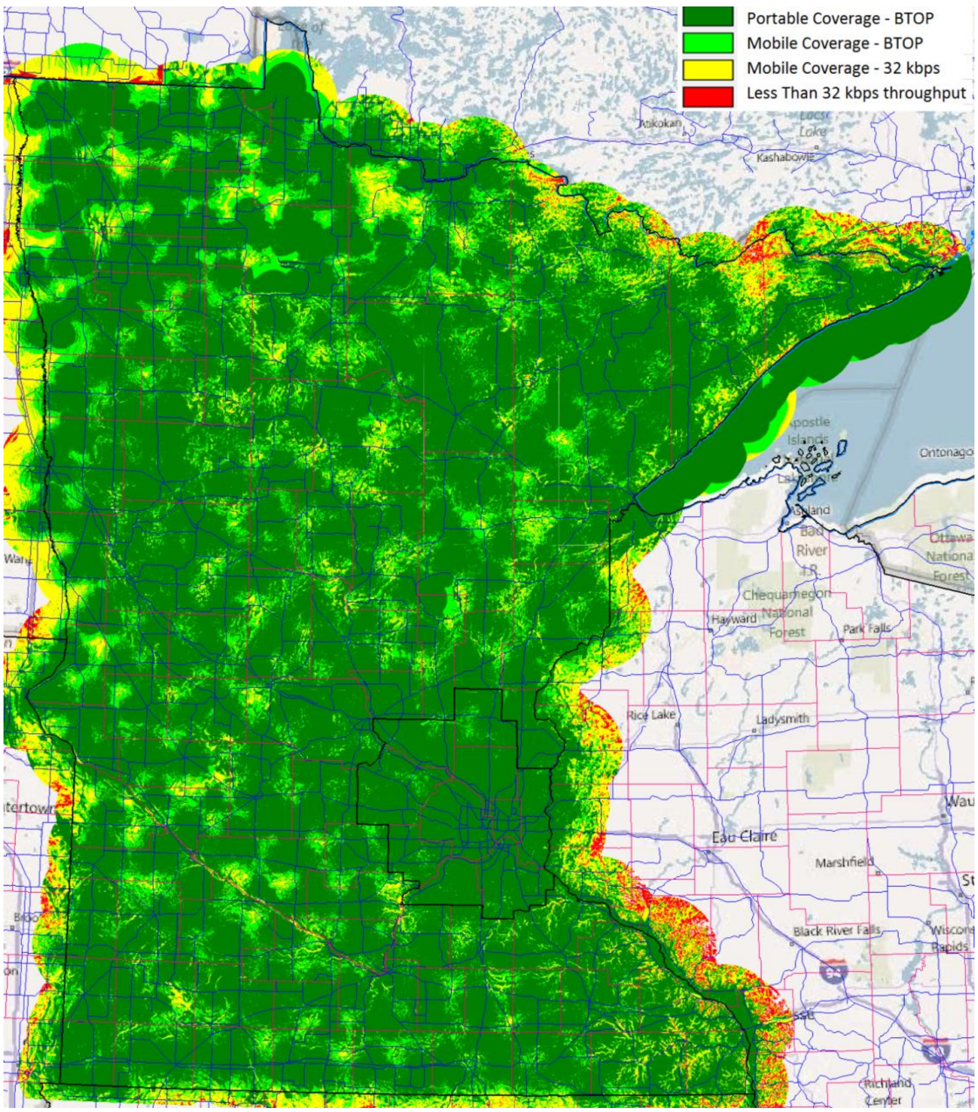

Figure 6: LTE Coverage Using ARMER Only Sites

Of the 28 counties that do not meet the 95 percent threshold, only six are covered in less than 89 percent of their area. The following table provides the six least covered counties.

Table 11: Counties covered the least in "ARMER Only Design"

County	Mobile Coverage (percent)
Cook	78%
Winona	82%
Lake	82%
Houston	84%
Lake of Woods	86%
Lac Qui Parle	85%

The above coverage maps depict the coverage at broadband throughput levels and using 16 percent of the host sector's resources. LTE can scale to lower throughput levels when the signal degrades. In other words, users in poor quality service areas may be able to secure low-speed coverage where broadband coverage is not available. The throughput will remaining high in areas with stronger coverage, however, in these areas with lower signal levels, some throughput is still available. If, for example, we consider a scenario whereby the required throughput is 32 kbps, multiple data applications could be available in these areas. Multiple applications can be supported at 32kbps for a single user, including text messaging, voice paging, database access, and web browsing. The figure above shows those areas that do not meet the BTOP throughput levels but do meet the 32 kbps criteria in yellow. The ARMER only configuration provides 95 percent mobile coverage for nearly all counties at this rate – only four counties in the following table fail to meet the 95 percent requirement at 32 kbps:

Table 12: Counties below 95 percent coverage at 32kbps (ARMER Sites only)

County	Mobile Coverage (percent) at 32kbps – ARMER Only Design
Lake of Woods	91%
Cook	92%
Winona	93%
Lake	94%

The ARMER Only Design meets the portable coverage requirements in all designated counties except in Isanti County where only 92 percent availability can be achieved. However, the ARMER Only Design greatly impacts the in-building coverage area in the major cities. These areas in and around Minneapolis and St. Paul are serviced with only 60 and 71 percent in-building coverage respectively. The figure below depicts the in-building service areas in dark green.

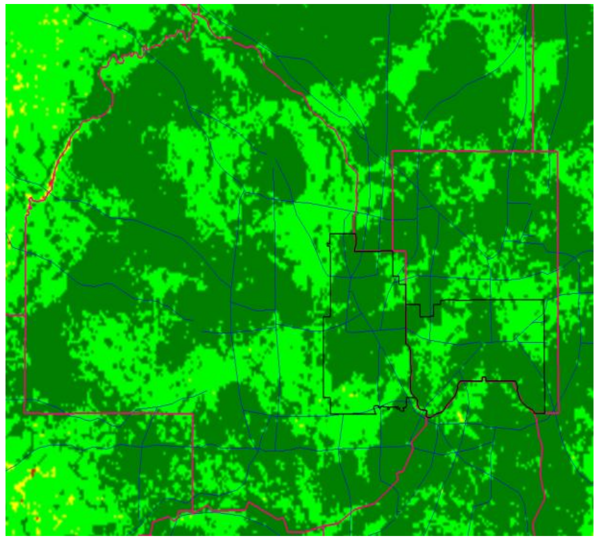

Figure 7: In-Building Coverage (ARMER Sites Only)

5.2.4 System Capacity

The preliminary design was optimized primarily for coverage. Televate did optimize the initial design for capacity; however, no additional sites were added due to a variety of unknowns. First, as identified in the needs assessment, it is unclear if the amount of incident demand is realistic. Second, the recent legislation that doubles the amount of public safety spectrum to 20 MHz will double the amount of available throughput. And third, the loading on adjacent sectors wherever these incidents occur can vary dramatically. If adjacent sectors need only support day-to-day traffic, the expected load is 10%. However, if other incidents occur on those adjacent sectors, the loading (percent of resources used) could hit 100 percent. Therefore, Televate has opted to show how the various scenarios impact the area over which the net load can be supported. The design seeks to minimize interference and therefore maximize system-wide throughput, however, at the intersection of two sectors, the signal-to-noise ratio will degrade as does throughput. The following figure depicts the worst-case scenario: all sites are transmitting at power[19], and are highly loaded.

[19] The downlink path uses power control. UE that are close to the site do not need much power to achieve high throughput levels, and therefore, the cell site will power down to minimize interference.

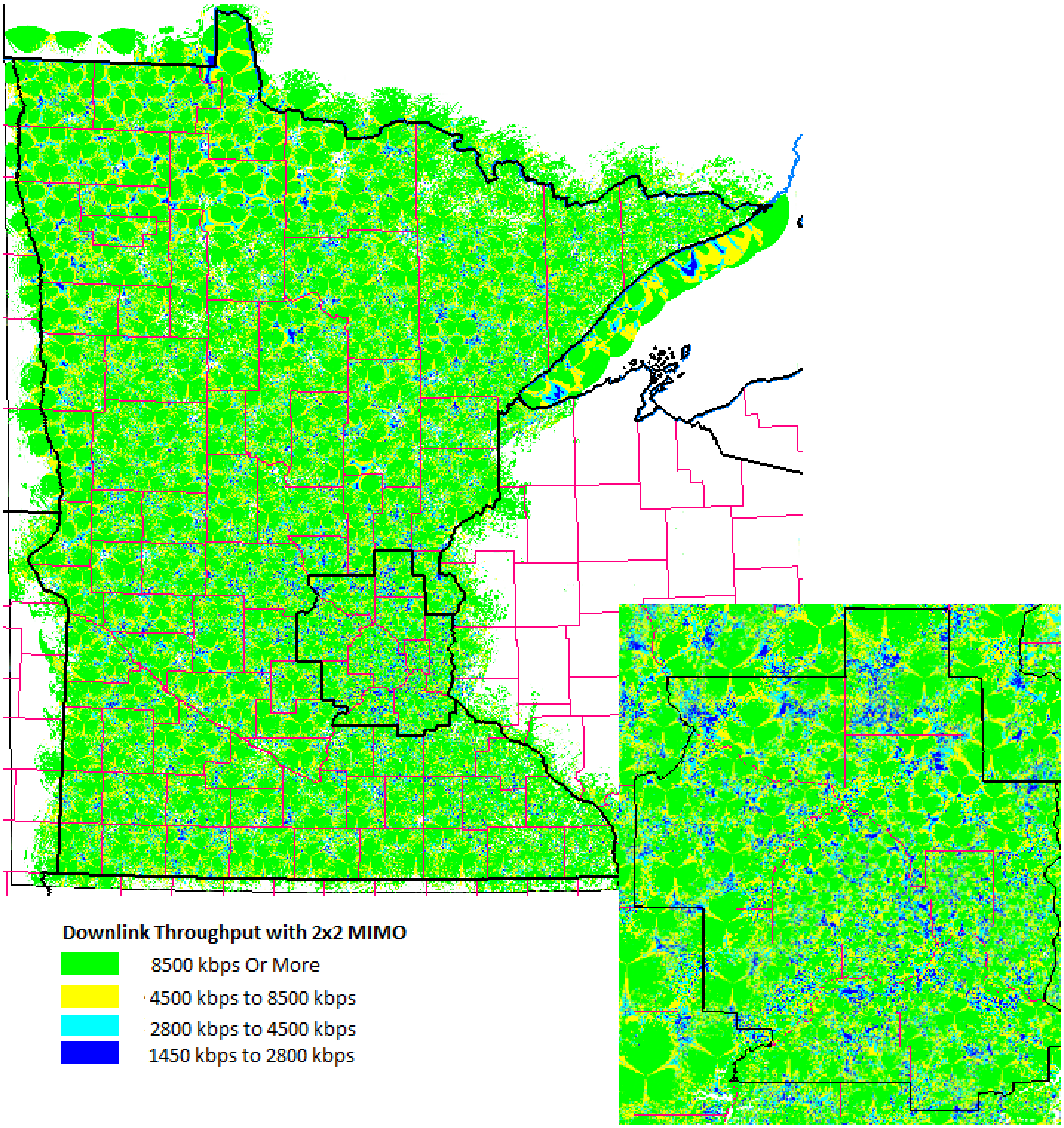

Figure 8: RAN Downlink Throughput Map

The figure above clearly shows the effects of intra-system interference between sectors. The figures depict that at the intersection of the signals between sectors, the throughput degrades to 1,450 kbps in a single sector. The design with this worst case scenario delivers 4,500 kbps on the downlink to an estimated 56 percent of the State using a 5 MHz channel. With an expected median cell throughput of 6.5 Mbps for the downlink and 3.1 Mbps for the uplink, a near term incident should be accommodated in typical areas.

The following table provides throughput statistics of RAN design:

Table 13: RAN Throughput Statistics Worst-Case Scenario

Throughput Level	Statewide	Urban (Target Portable Service Area)
8,500 kbps or More	59 %	52 %
4,500 kbps to 8,500 kbps	82 %	77 %
2,800 kbps to 4,500 kbps	93 %	93 %
1,450 kbps to 2,800 kbps	96 %	99 %
950 kbps to 1,450 kbps	98 %	99 %

Table 12 above shows the per sector rural incident throughput of 2,810 kbps is available in 93 percent of the State. The short-term target urban area incident throughput of 4,311 kbps is met in a little over 93 percent of the urban areas. The long-term urban throughput requirement of 8,508 kbps is achieved in more than 82 percent of the State.

The map and statistics represent the capacity of only one sector, and therefore, the analysis assumes the incident is confined to one sector. An incident may cover an area that encompasses multiple sectors, and therefore, their combined capacity can be leveraged. The FCC's capacity white paper made such an assumption. In fact, the FCC's modeling was of the Twin Cities I-35 bridge collapse. The FCC assumed that the capacity was spread over six sectors and one square mile, and therefore, the load offered to one sector was sixth (1/6) of the total load. However, the incident modeled in the Needs Assessment was project to span an area of 0.02 square miles. The design for the twin cities area projected that a typical urban sector serves four square miles. Hence, there is little probability that such an incident could span more than two adjacent sectors. In a scenario where multiple sectors service such an incident, the incident would occur at the cell edge where the throughput is lowest due to low signal-to-noise ratios, and therefore, the spectral efficiency is at its lowest. Televate uses the single sector capacity to gain perspective on the worst-case scenario to accommodate the incidents.

The map and statistics shows that with a "perfect storm" of multiple simultaneous and adjacent incidents even with 20 MHz of spectrum, the design does not meet the long-term capacity requirements. However, the following table provides certain scenarios in which the capacity needs of the state can be reliably met:

Table 14: Capacity Availability Scenarios

Incident Type Downlink Throughput	Adjacent Cells Loading	Spectrum	Statewide Availability
Urban Short Term (4.5 Mbps)	70%	20 MHz	89%
	10%	20 MHz	99%
Rural Short Term (2.8 Mbps)	70%	20 MHz	96 %
	10%	20 MHz	99%
Urban Long Term (8.5 Mbps)	70%	20 MHz	59%
	10%	20 MHz	63%
Urban Long Term (8.5 Mbps) includes LTE Advanced spectral efficiency[20]	10%	20 MHz	84%
	70%	20 MHz	72%

The table clearly demonstrates the impact of loading on adjacent sectors and the effects of much higher incident throughput. The lighter demand of the rural scenario should be more easily accommodated with the 20 MHz total allocation. However as the adjacent sector load and incident scale increase, the design leaves increasing portions of the state with insufficient capacity. Resolving this deficiency requires the performance enhancements of LTE Advanced. But even this improvement has limited effects. Ultimately, if system throughput cannot be enhanced via technology improvements, the system would require cell-splitting, more sites – reducing the adjacent sector loads and their interference.

The main driver in the capacity consumption at the incident is video. Based on the type of the incident and depending on the number of video streams that need to be sent simultaneously, the commanders at the scene may consider using a lower quality video to accommodate the limited bandwidth availability. LTE's advanced capabilities regarding priority and pre-emption can also ensure that the priority traffic can get through. These maps and statistics underscore the importance of capacity management.

5.2.5 Other Coverage and Capacity Mitigation Strategies

In addition to adding cell sites to accommodate any coverage or capacity deficiencies in the design, the State could opt to deploy a number of other strategies that can improve both. The strategies include:

- In-building systems: these solutions augment signal levels inside a building. As a result, the improvement in signal-to-noise ratio improves coverage and capacity; for example, a BDA (Bi-Directional Amplifier).

[20] Also assumes the spectral efficiency gains of LTE Advanced, expected in the 2013-2015 timeframe.

- Cell-on-wheels (COW): these portable cell sites (eNodeBs) with on-board backhaul (e.g., satellite) enable a site to be added to the system to address an incident or outage in the system. Because the site can be located nearby an incident, it's capacity can be very high.
- Relays: similar to a COW, the relay essentially serves as another cell site, however, the backhaul itself comes from the LTE network, and therefore, is simplier to establish than alternative methods.
- Self-Organizing Networks (SON): the 3GPP standardized feature will automatically adjust system parameters to load-balance and otherwise optimize the network to accommodate the demand. It can also help to mitigate the impacts of failures.

These techniques are fully described in the Appendix.

5.3 Backhaul Design

The review of the State assets showed the backhaul infrastructure currently available includes the fiber network as well as microwave links. The proposed design leverages those assets as much as possible. The proposed backhaul design addresses the following basic requirements:

- The network is all-IP and supports low latency traffic as required by LTE
- Backhaul from each site needs to support the incident and day-to-day capacity
- Can utilize scalable infrastructure to support future capacity growth.
- The backhaul architecture does not include a single point of failure.
- The design leverages the existing assets as much as possible.

The following sections describe the existing infrastructure and the proposed backhaul design.

5.3.1 Description of Existing Backhaul Infrastructure

The ARMER backhaul consists mainly of microwave links varying from 8-DS1 (12 Mbps) to 1-OC3 (155 Mbps). According to the ARMER Integration Report, the ARMER microwave network has 99.999 percent (five nines)[21] reliability through loop protection, alternate-path routing, and space diversity. However, there is no excess capacity[22] available on the existing ARMER microwave network for LTE use. Therefore while there may be some feasibility to share some infrastructure (e.g., antennas), the broadband implantation model assumed that new microwave hardware is required. However, the model assumes that the State's fiber optic network can be used to carry the traffic from each region, back to the Evolved Packet Core (EPC).

The LTE network will integrate with the Minnesota's Network for Enterprise Telecommunications (MNET). MNET provides fiber POPs (Points of Presence) at multiple locations in the State. Sites at or

[21] State of Minnesota Department of Public Safety Public Safety Network Integration Study, BearingPoint

[22] Idem

near the POPs will connect to the EPC via the fiber ring. They should also serve as the aggregation points for other sites.

5.3.2 Microwave Design Overview

The technologies typically used to support wireless broadband throughput requirements are either fiber or IP microwave systems. Due to the excessive cost of fiber, the implementation model uses microwave where new connectivity is needed. In addition to providing scalability and high throughputs, IP microwave exploits Adaptive Coding and Modulation (ACM) schemes and statistical multiplexing to better manage IP traffic over the radio link. The proposed IP microwave provides up to 100 Mbps on each link with 30MHz channel bandwidth at 99.9999 percent availability. In Metro Region where high capacity demand is expected in the future, the solution can be scaled by adding a second 30MHz channel radio. Capacity can also be increased by using antenna cross polarization. This technique has the advantage of doubling the capacity within existing spectrum allocations, but it comes at double the cost of the initial link.

The frequency bands available for licensed microwave links include 6 GHz, 11 GHz, 18 GHz and 23 GHz bands. All other parameters being equal, the maximum achievable distance of a microwave link decreases as the frequency increases. Therefore, it is recommended to use higher frequencies for shorter hops and lower frequencies for longer hops. During the backhaul design of Southwest Region 6 GHz and 11 GHz were chosen as the primary microwave frequencies. This should apply to other rural areas. However in Metro Region, 18 and 23 GHz links should be used for the shorter hops. Televate used an iterative design process to determine the best frequency band to use for each link to achieve the target throughput with 99.9999 percent availability. Table 14 below depicts the recommended microwave configurations throughout the State.

Table 15: Microwave Frequency Band Recommendations

Microwave Link Range	Frequency Band Recommended
Less than 3 miles	6, 11, 18 or 23 GHz
3 Miles to 7.5 miles	6 or 11 GHz
More than 7.5 miles	6 GHz

The design assumed a typical IP microwave radio using between 5 to 30 MHz channel width for the 6 GHz bands and 5 to 40 MHz channels for the 11/18/23 GHz bands. Televate's design assumed tower mounted microwave amplifiers to reduce cable loss and improving the link budget of the microwave system.

Figure 9: Sample Microwave Radio and Integrated Antenna

Licensed wireless backhaul solutions are also available in the 4.9 GHz band for public safety use.[23] However, this amount of spectrum is deemed insufficient to accommodate the needed

[23] FCC Rules Part 90, Subpart Y, 90.1207

capacity and frequency reuse. The proposed microwave design requires 30 MHz channel bandwidth for each radio to support the full capacity of the LTE sites on each ring in urban areas. Finding that amount of bandwidth for the exclusive use of the State will be challenging. However, 4.9GHz can be an option in the State's microwave deployment where spectrum is not available.

5.3.3 Proposed Backhaul Architecture

Figure 11 depicts the proposed backhaul topology for the Southwest region. The proposed backhaul network is fault tolerant and leverages the fiber links available in the region to backhaul the traffic to the core. A detailed backhaul design for the rest of the State is not part of the scope; however Televate recommends the same design approach to ensure maximum system reliability. A maximum number of microwave sites should have no less than two separate routable paths back to the Evolved Packet Core. In some situations, especially at the edge of the network, path redundancy may not be possible. In these cases, other methods should be considered to provide higher reliability. For instance, additional links on the same path can be used to overcome outage situations due to hardware failure or frequency selective fading.

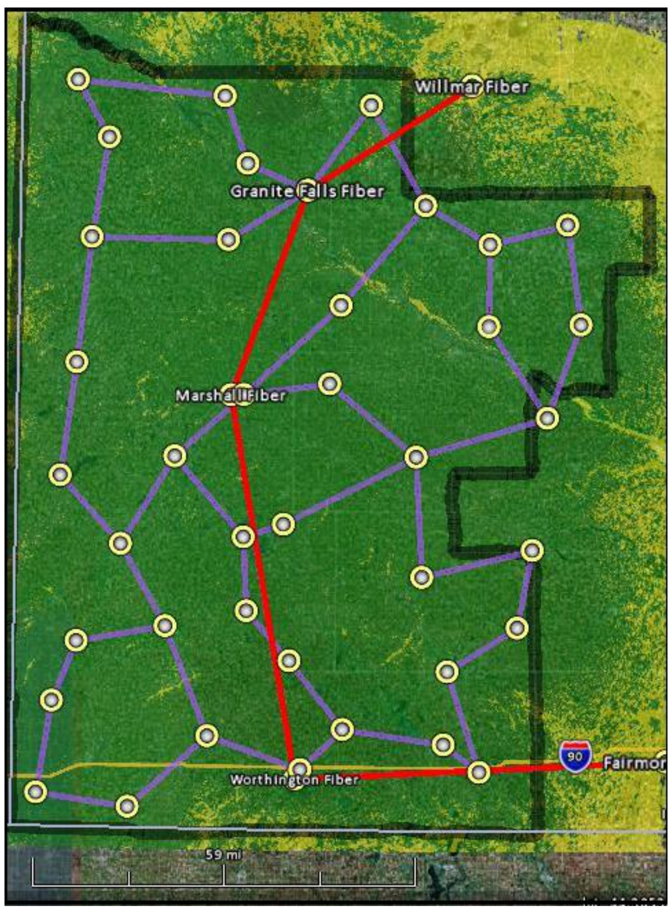

Figure 10: Proposed Backhaul Topology in the Southwest

The backhaul design shows that with only four points of presence it is difficult to design the rings so that every ring itself intersects at to fiber points-of-presence (POPs). Therefore, the rings themselves must be interconnected with a POP. Furthermore, interconnected rings are necessary in order to achieve multiple interconnection points with the fiber ring. Otherwise, rings could have single points of failure where they interconnect with the fiber network. It is also important to note that the coordinates for the Marshall and Worthington POPs do not precisely match those of the Marshall and Worthington radio towers. The model and design presumes these are co-located. In the event they are not, additional backhaul facilities would be required.

The proposed design results in 1.2 microwave links per site. It requires, at the most, nine sites to be backhauled on a single link, and therefore, the microwave capacity must satisfy nine sites worth of traffic. The net impact of the Southwest region on the fiber network is over 3.2 Mbps per site or 139 Mbps. The other regions would have a similar impact on the fiber network, however, the urban impact is expected to be 11.7 Mbps per site, and therefore, the Metro region would generate 1,235 Mbps. These figures represent the long-term incident scenarios, and therefore, this fiber capacity would occur over a 10 year period. However, these calculations assume that all traffic generated at the cell sites must traverse the Evolved Packet Core. In future releases of LTE, new features enable local offloading of traffic. Application traffic generated in Marshall, for example, which is hosted on servers in Marshall, could be dropped directly to local servers instead of riding the fiber ring (see OET backhaul architecture below). Therefore, the net impact on the fiber ring will depend on the expected distribution and destination of the LTE user traffic.

Figure 11 - OET Long-Haul Fiber Network

There were two design backhaul scenarios. The first seeks to maximize microwave connections and only use OET connections for long-haul circuits. The second scenario seeks to maximize OET or local fiber connections. Both design scenarios were overlaid on the OET fiber network. In the first instance, OET's network was only used for the connectivity of the regions to the core network locations. In the second instance, microwave point to point connections were minimized and OET connections were maximized. Fiber connections from the county entities were also included into the design.

This process entailed a detailed review of two counties from the Twin cities region, Douglas and Scott counties. The ARMER site locations for these counties are considered key assets and consequently they are used for multiple public safety related services. Likewise, the county IT departments have endeavored to extend their fiber connections directly to the towers in most cases. In review of Douglas and Scott county fiber connectivity, it was determined that 95 percent of the ARMER locations had access to a fiber connection. Extending the methodology statewide discovered an estimated 126

ARMER sites, or 33 percent, with some type of fiber connectivity, either directly with OET, the county or local municipality.

5.4 Core Network Configuration

Televate recommends the LTE Network include the Evolved Packet Cores (EPC) at two separate locations to ensure geographical redundancy as shown in Figure 1. Each EPC should be located on the State's existing fiber ring[24]. It is suggested that geographical redundancy be achieved by placing the primary core located in the Metro Region and the secondary core network in another hardened facility. The following connections will be required:

- Connection between all eNodeB sites to each core via the backhaul network
- Diverse path connection between the two cores
- Connection of each core to the external networks including the nationwide public safety LTE network, the Internet, and other public safety networks

6 High Level Budget Estimates

The implementation model contains high level budget projections for both capital costs and operating costs. The following sections provide the assumptions upon which those projections are based and the resulting financial estimates.

6.1 Capital Cost Assumptions

The capital budget includes all foreseen activities required for the successful deployment of a 521 site LTE network. The itemized hardware components and the associated costs for their installation and integration are included in the various budgetary categories. Engineering, project management, and other service costs from vendors are accounted for within the budget; the budget also includes engineering support costs incurred by the State to support the integration onto existing systems as well as the leveraging of State infrastructure. The budget includes the following categories:

- eNodeB, antenna system and supplemental coverage solutions (with integrated UPS and HVAC systems in a custom enclosure)
- Backhaul network and network equipment
- OET connection to core networks
- New towers and existing site remediation costs
- Generators

[24] The redundant EPC could also be located beyond the State of Minnesota boundary.

- Facilities work, permitting and construction estimates
- Network and engineering professional services
- Core network, NOC and internetwork costs
- Contingency budget and taxes

Where applicable, the cost estimates used historical ARMER deployment and operations costs. Specifically, Televate leveraged the following ARMER-based reports and studies:

- Annual ARMER Maintenance and Operations Plan
- ARMER Phases 4-5-6 Cost Audit Report
- Public Safety Network Integration Study

6.1.1 Sites Construction

The most significant financial aspect of the models is the Capital cost which includes the cost to construct tower sites. As presented earlier in the design section, 141 of the 521 sites are new sites with the following assumptions:

Table 16: Site Assumptions

Type of site	Number of Sites	Assumption
New Sites	141	■ Land is purchased to build each of these non-ARMER sites ■ Each site requires installation of a generator ■ Construction costs of each new site is equal to historical ARMER costs ■ The new sites will not generate revenue (from lease by third party)
Existing ARMER Sites (Towers)	364	■ Most existing ARMER sites do not require rent ■ No structural reinforcement needed on existing ARMER sites to support new LTE antennas ■ 10 percent of ARMER sites will require a new generator
Existing ARMER Sites (Buildings)	16	■ Half of the building sites are owned by the State and do not require rent costs. Half require rent cost

6.1.2 Internet Connectivity

Public safety subscribers will need access to the Internet. This includes not only the State users but also the mutual aid responders. Among the applications user agencies plan to deploy by 2015, those expected to use internet include:

- Mapping or Geospatial data
- Web browsing
- Access to home enterprise servers
- Access to email
- Software and Operating System Updates
- Database lookups and fingerprint retrieval

The model assumes the Internet will be accessed through agency home networks. The internet access will not be provided via the EPC and the cost will be borne by individual agencies. However, when users roam in to and out of the statewide private network, capacity is needed between the State's EPC and the roaming partner's core network. This roaming "backhaul" between the State's network and the roaming partner is included in the model.

6.1.3 Spares

The model requires spares since the State owns the responsibility to maintain the system in a timely manner. We assume that 10 percent of all electronic hardware, including backhaul equipment, eNodeBs, and EPC is required to establish an inventory of spares.

6.2 Capital Expenditure Estimate

The capital expenditure costs are summarized within two models; the ARMER PLUS and the ARMER models. The ARMER PLUS includes the 521 sites required to meet the State's capacity and coverage requirements. The ARMER model includes the 380 ARMER sites and excludes the 141 new sites added in the previous model. The cost estimates of both models are as follows:

Table 17: CAPEX Estimates

Maximized Microwave Connections	ARMER Plus (521 Sites)	ARMER (380 Sites)
Radio Access Network & Install	$ 108,605,378	$ 81,151,348
Backhaul / IP Network & Install	$ 92,870,512	$ 68,259,973
Tower and Construction Costs	$ 63,628,400	$ 5,334,107
Core Network	$ 21,419,800	$ 19,994,200
Supplemental Coverage Solutions	$ 2,500,000	$ 2,500,000
State Tax	$ 15,607,394	$ 8,996,624
Contingency Budget	$ 27,505,321	$ 16,586,651
CAPEX Grand Total	**$ 332,136,804**	**$ 202,822,903**

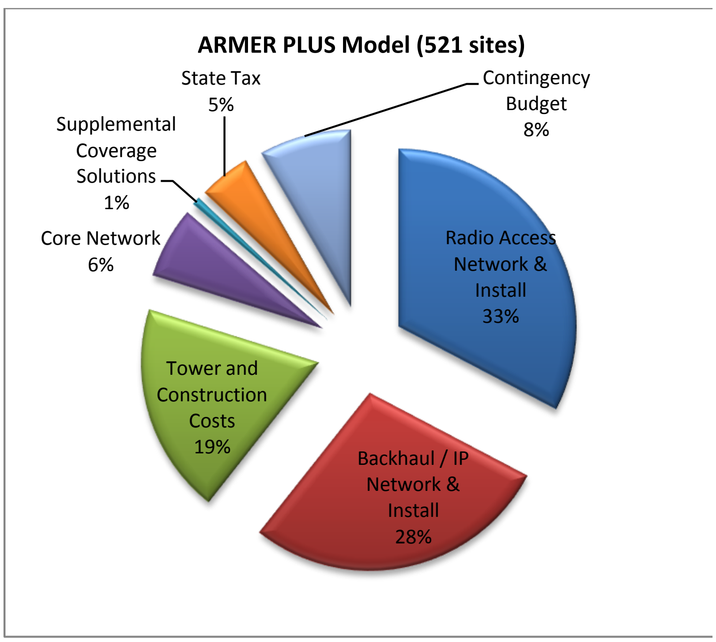

Figure 12 - CAPEX Breakout of 521 Sites

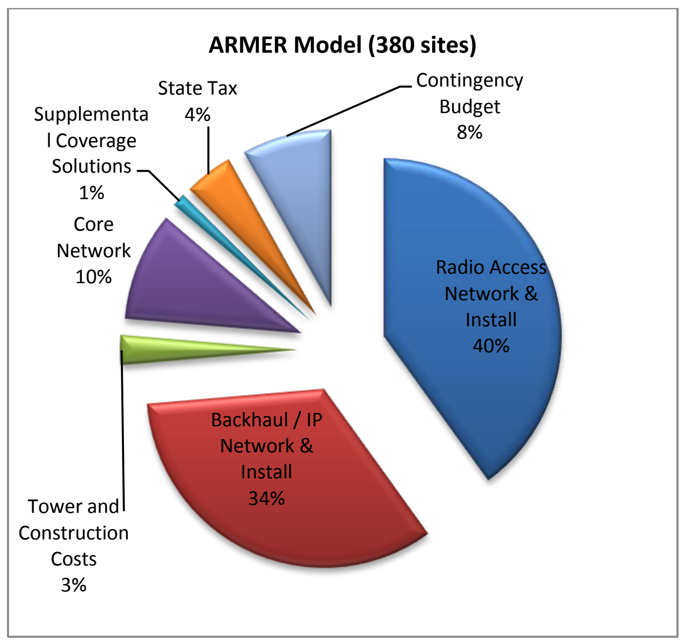

Figure 13 - CAPEX Breakout of 380 Sites

With the exception of the Core Network and Supplemental Coverage Solutions, there were across the board reductions in cost for the 380-site ARMER Model. Using the ARMER Model saves the cost of building 141 new towers, a $59 million savings. All other costs are generally reduced proportionally due to the reduction of site numbers overall.

The table highlights the impact of the Radio Access Network on the costs. The significant number of RAN sites impacts eNodeB, microwave, and tower and construction costs.

Table 18: CAPEX Estimates for Maximized OET connections

Maximize OET Connections		ARMER Plus (521 Sites)		ARMER (380 Sites)
Radio Access Network & Install	$	108,605,378	$	81,151,348
Backhaul / IP Network & Install	$	77,954,091	$	53,343,552
Tower and Construction Costs	$	63,628,400	$	5,334,107
Core Network	$	21,419,800	$	19,994,200
Supplemental Coverage Solutions	$	2,500,000	$	2,500,000
State Tax	$	14,622,910	$	8,012,140
Contingency Budget	$	26,013,679	$	15,095,009
CAPEX Grand Total	**$**	**314,744,258**	**$**	**185,430,356**

By maximizing the OET connections, the capital expenditures were reduced by $17,392,547.00 or six percent.

6.3 Operating Cost Assumptions

The operations cost analysis is equally thorough and have included all costs foreseen for the efficient operation of the network. Televate incorporated the same resources as mentioned above into the cost study. This and other categories of expenses are itemized as follows:

- Rent, leases, utilities and facilities maintenance
- Software licenses, patches and monitoring
- A full accounting of operations personnel inclusive of training
- Roaming costs
- Annual vendor operations and maintenance support

6.3.1 Personnel

In the model we assume that space, administrative staff and other overhead costs must be covered. It is feasible that the leveraging of the existing government resources could save money, but it would not eliminate the expenses completely. Therefore, the model assumes that these costs must be borne by the operations and that they are the same whether the model is private internal or non-profit owned (via a public-private-partnership). To provide a conservative estimate, the model assumes that the LTE operations would be new and separate with no cross-system responsibilities between the existing

ARMER and LTE operations team. As a result, the budget assumes a more than doubling of operations personnel with more than 54 new supervisors, monitoring and maintenance technicians hired as detailed in the following list:

- 1 LTE Operations Manager
- 5 Regional Operations Managers
- 8 24/7 Monitoring Personnel
- 34 Maintenance Field Technicians
- 3 Provisioning and Customer Support Team
- 3 Network Support Engineers

6.3.2 Training and Technical Support

The model includes ongoing training of the entire team for the LTE network. Depending on their responsibilities, the model includes one or two weeks of off-site LTE training per annum per new engineer; for a total of 65 weeks.. Also included in the model is the infrastructure vendor technical support. This will cover software maintenance such as routine patches and upgrades.

6.3.3 Subscriber Devices

The model assumes that the private model devices cost are provided at a premium. Commercial devices such as USB modems often are provided free with a two-year contract, however, a Private Service model does not include subsidies from a commercial carrier. The following table provides a summary of our assumptions regarding subscriber device costs for Band Class 14:

Table 19: Estimated Device Costs

Device Type	Price
Aircard (PC Card) Modem	$500.00
AVL Modem	$1000.00
Embedded Modem (installed in notebook PC)	$500.00

Like with ARMER, we assume that the cost of the devices will be borne by the individual agencies and is excluded from capital and operating estimates. However, the cost is included in comparisons with commercial services costs to account for the carrier subsidies.

6.3.4 Roaming

The model assumes one percent of all 100,000 users will need out-of-State roaming and will consume 1100 MB (megabytes) per month per user. This “budget” can also accommodate internal roaming – areas where State provided coverage (e.g., inside a building) is inadequate yet commercial service is available. This usage will require compensation from the commercial network partner. It is possible that such roaming could eventually be on another private, public safety network; however, for now we assume that this is not the case, and therefore, we must budget for roaming on to a commercial network.

6.4 Operations Expenditure Estimate

The operations expenditure costs are summarized for the two models defined above: the ARMER PLUS and the ARMER models. Both models assume an equal number of subscribers (100,000) an equally sized core network and operations staff. The variance between the two operational expense totals is due to the proportional reduction of software licenses and maintenance costs for the smaller 380 site network.

Table 20: OPEX Estimates

Maximized Microwave Connections	ARMER Plus (521 Sites)	ARMER (380 Sites)
Facilities Costs & Rent	$ 3,794,532	$ 3,603,700
Network Maintenance	$ 1,563,000	$ 1,140,000
Software Licenses & Patches	$ 1,455,000	$ 1,158,900
Operations Personnel	$ 3,485,900	$ 3,485,900
Annual Roaming Costs	$ 2,500,000	$ 2,500,000
Contingency Budget	$ 1,279,843	$ 1,188,850
OPEX Grand Total	$ 14,078,275	$ 13,077,350

For simplicity, the model did not modify the staff required to operate the smaller, ARMER only, network. It is feasible that this budget could be reduced. However, we might expect that the reduced number of sites may also increase the roaming costs. With reduced coverage in the urban areas (lack of building penetration), more users may find themselves roaming on to commercial networks in the urban areas – potentially offsetting any staffing reductions.

Table 21: OPEX Estimates for Maximized OET connections

Maximize OET Connections	OET ARMER Plus (521 Sites)	OET ARMER (380 Sites)
Facilities Costs & Rent	$ 5,460,582	$ 5,269,750
Network Maintenance	$ 1,563,000	$ 1,140,000
Software Licenses & Patches	$ 1,455,000	$ 1,158,900
Operations Personnel	$ 3,485,900	$ 3,485,900
Annual Roaming Costs	$ 2,500,000	$ 2,500,000
Contingency Budget	$ 1,446,448	$ 1,355,455
OPEX Grand Total	$ 15,910,930	$ 14,910,005

The second scenario, that maximizes the number of connections to the OET fiber network, resulted in an increase of $1,832,655 of operational expenses. This represents an increase of 12 percent over the other scenario. This cost is associated with supporting the network connections at the State and County levels.

6.5 Breakeven Analysis

Televate calculated the breakeven points for the implementation cost per subscriber for both the ARMER PLUS (shown as “ARMER+” in Figure 17) and ARMER models. The breakeven calculations consider the cost of the network as well as the amortization costs of equipment and infrastructure. While the funds to build the network may be furnished through grant funding, the inclusion of amortization of the capital expenses provides a perspective of the full cost of the service. The model assumes amortization of ten (10) years for electronics, 20 years for services, and thirty (30) years for facilities improvements (e.g., towers). The following table and graph provides the results of the breakeven calculation and the minimum number of subscribers required to support the network costs.

To establish the basis of the breakeven point, we assume a monthly contract rate of $46.27 ($42.99 plus 7.625% sales tax). The contract rate is for typical 4G (LTE) wireless data services. The breakeven calculation assumes a free device from the service provider and no installation costs. No supplemental costs were added for priority or preemptive services on the carrier’s network, which should increase the monthly fees.

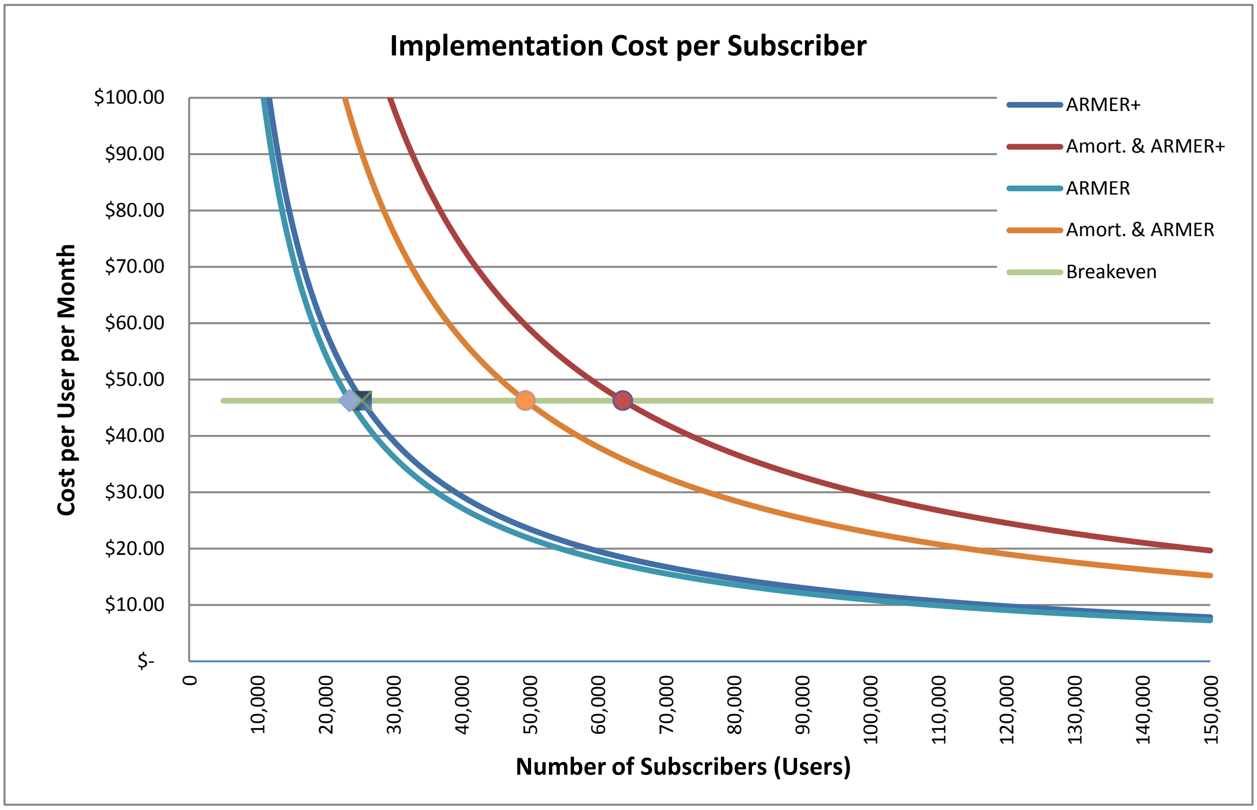

Figure 14: Breakeven Calculation Graph

The point at which each curve, representing the monthly operational costs per user for the various scenarios, intersects the fixed monthly cost per user represents the breakeven point for that scenario. The figure illustrates that the State would require a substantial number of users to match commercial operating costs.

Table 22: Breakeven Points

Breakeven Thresholds	Number of Subscribers
ARMER PLUS with Amortization	63,694
ARMER PLUS without Amortization	25,356
ARMER with Amortization	49,387
ARMER without Amortization	23,554

These figures should be compared against the total expected user population for a statewide broadband network. Corollaries to the number of ARMER P25 subscribers provide a helpful estimate for the potential quantities. However, such figures need to be measured against agencies' ability to fund the subscriber devices and applications needed to derive the full benefit of a statewide broadband network.

Furthermore, while many agencies may opt to deploy a mobile P25 subscriber in a vehicle and a portable P25 radio to a user, there may be scenarios that necessitate more broadband devices on a per user basis. For example, an agency may opt to equip each vehicle with a broadband modem for tracking and maintenance purposes, each laptop with a modem as fully-functional field device, as well as a handheld PDA, smartphone, or tablet. Agencies may also choose to embed broadband modems in other devices such as video cameras and EKGs. A thorough analysis of the public safety needs across the State will shed light on plausible user base and the potential economic impact of a statewide broadband network.

The state has assumed that a minimum of 100,000 users would be migrated to the LTE network. Based on this assumption and the cost figures within the budget, the resulting cost per subscriber is displayed in the following table:

Table 23: Breakeven Points

Cost per 100,000 Subscribers	Cost/Sub
ARMER PLUS with Amortization	$ 29.47
ARMER with Amortization	$ 22.85
ARMER PLUS without Amortization	$ 11.73
ARMER without Amortization	$ 10.90

7 APPENDIX

7.1 LTE System Description

LTE consists of a flat all-IP architecture. The Radio Access Network (RAN) includes a set of base stations (eNodeB) connected to the Serving Gateway that manages the routing to mobile devices and eNodeBs. The Home Subscriber Server (HSS) acts as an Authentication Authorization and Accounting (AAA) entity while the Mobile Management Entity (MME) manages the device's mobility. The Packet Data Network (PDN) Gateway connects to other IP Networks.

eNodeB

In LTE, the Radio Access Network (E-UTRAN) is reduced to only a set of base stations transmitters and receivers called eNodeB. The eNodeBs are IP devices and include routing functions.

Mobility Management Entity (MME)

The Mobility Management Entity (MME) is responsible for idle mode UE (User Equipment) tracking and paging procedure including retransmissions. It is involved in the bearer activation/deactivation process and is also responsible for choosing the Serving Gateway (S-GW) for a UE during the session setup process.

Serving Gateway (SG-W)

The Serving Gateway (S-GW) routes and forwards user data packets, while also acting as the mobility anchor for the user plane during inter-eNodeB handovers. For idle state User Equipment, the SGW terminates the DL data path and triggers paging when DL data arrives for the UE. It manages and stores UE contexts, e.g. parameters of the IP bearer service, network internal routing information. It also performs replication of the user traffic in case of lawful interception.

Packet Data Gateway (PGW)

The Packet Data Network Gateway (P-GW) provides connectivity from the UE to external packet data networks by being the point of exit and entry of traffic for the UE. It provides UE IP address management. A UE may have simultaneous connectivity with more than one P-GW for accessing multiple Packet Data Networks (PDNs). The P-GW performs policy enforcement, packet filtering for each user, charging support, lawful Interception and packet screening.

Policy and Charging Rules Function (PCRF)

The Policy and Charging Rules Function (PCRF) provides dynamic control of QoS, gating and charging policies. It allows applications to dynamically request QoS characteristics for LTE bearers. It uses an Rx interface to application layer servers to coordinate session QoS with services provided by the application layer.

Home Subscriber Server (HSS)

HSS is the master database that contains the subscription-related information (user profiles), performs authentication and authorization of the user, and can provide information about the user's physical location. It is responsible for storing the following user-related information:

7.2 RAN Coverage Statistics

The following table provides the high level statistics of the design:

Table 24: LTE Design Coverage Statistics

Coverage Area	Coverage Statistics	Coverage Type
Greater Minnesota	More than 95percent in each County	Outdoor Mobile Coverage
Hennepin **Ramsey** **Washington** **Anoka** **Isanti** **Sherburne** **Wright** **Carver** **Scott** **Dakota**	99% 99% 98% 98% 95% 98% 98% 98% 99% 99%	Hip-Worn Device Coverage
Minneapolis **St Paul** **Rochester** **Duluth** **St. Cloud**	98% 97% 96% 95% 97%	In-Building Coverage

7.3 Coverage and Capacity Solutions

Emergency situations may require the network to support user traffic that exceeds the intended capacity as multiple agencies respond at an incident scene. Additionally, the incident can occur in the five percent of geographic areas not intended for coverage in this design or inside a tunnel or building where the penetration loss exceeds the amount assumed in the design. In all those cases, the ability to provide portable, quickly deployable solutions to the particular area will be crucial. If the State decides in the first phase to deploy LTE only on the existing ARMER facilities, coverage augmentation strategies will be even more necessary to meet the user demands during incidents. Some potential coverage and capacity enhancement solutions are provided below.

In-Building solutions

The proposed RF design will provide in-building coverage in the major cities. In rural areas, even though the network is engineered for mobile coverage, it attempts to provide as much in-building coverage as possible by strategically locating sites near inhabited areas. However there will be situations where the required building penetration is higher (parking tunnels, thick building walls, and others). In order to avoid the costly deployment of additional sites to provide such coverage, it is possible to implement a local in-building coverage solution as an alternative. An in-building coverage solution system, example Bi-Directional Amplifier (BDA), receives the signal from the base station, amplifies it then retransmits it inside the building. In a similar fashion, the system amplifies signals it receives from indoor users to retransmit to the base station. These systems must be installed exactly where coverage is needed and their design must consider the spectrum environment so the signal for other operators is not amplified. Furthermore there must be enough isolation between the donor and coverage antennas to avoid self-interference that would drive down the SNR, and therefore lead to poor performance.

COWs and COLTs

The State can use deployable equipment during an emergency to extend coverage in areas not covered. Or it could use deployable equipment to replace a damaged site or to support excess traffic. This equipment consists of a temporary cell site mounted on a truck portable tower commonly referred to as a cell on wheels (COWs) or cell on light trucks (COLTS). The temporary site is backhauled, either via a satellite link or a point-to-point microwave solution. Note that deployable assets operating in the public safety broadband spectrum are required to comply with the technical and operational rules established for that spectrum, e.g. the maximum transmit power. The State may decide to purchase a certain number of COWs and store them in each region so they can be used when needed. Because of the size of the State, COWs should be strategically stored to reduce the emergency response time.

Relays

Available in 3GPP Release 10, LTE Relays can be used to improve the quality and coverage of the network at the cell edge. They are easy to deploy as they do not require additional backhaul links like COWs and COLTs described above. A Relay differs from a repeater in that it receives the data, demodulates and applies any error correction before re-transmitting the signal. The SNR and the signal level are both enhanced which is not necessarily the case when using a repeater. A LTE relay is connected wirelessly to the nearest base station, in-band or out-band. In-band relays use a portion of the radio resources of the donor base station for backhaul. This has the advantage of backward compatibility as it allows Release 8 UEs to connect to the donor cell.

Self-Organizing Networks (SONs)

The Self-Organizing Network (SON) feature simplifies operational tasks through automated mechanisms such as self-configuration and self-optimization. Self-optimization consists of changing radio parameters on the fly without human intervention. SON also provides a self-healing feature that automatically identifies faults in the network. For instance, when a site fails, SON feature creates new associations between healthy network elements while avoiding service interruption. Users from the faulty cell can also be relocated to other cells by adjusting coverage and handover related parameters of the nearby cells.